Evaluating Realistic Volume Scattering Functions on Underwater Imaging System Performance

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LONG-TERM GOALS

The Navy has a continuing and pressing need to improve its ability to visually detect and identify underwater objects. As far as imaging environments go, this is one of the worst: absorption and scattering by the water and the dissolved and particulate within rob a system of its signal and blur the resulting image. Sophisticated systems like the Laser Line Scanner (LLS) and the Streak-Tube Imaging LIDAR (STIL) have been designed and engineered to address some of these difficulties. But while engineering properties of an imaging system can be decided upon and controlled to a certain extent, it is most often the variable environmental conditions that are the limiting factors to system performance and, ultimately, utility. Our goal is to evaluate the effects of these environmental conditions on the performance of underwater imaging systems.

OBJECTIVES

A great deal of work has been done in analyzing and evaluating the effects of the *strength* of scattering and absorption on underwater systems, and the best system geometries and imaging modalities to address these issues. There has, however, been very little work in examining the effects of the *angular distribution* of the scattered light. This is due in no small part to the current want of measurements that describe this distribution, the volume scattering function (VSF). As a result, most imaging models and systems use either mathematical approximation of the VSF or the commonly used measurements of Petzold [1]. But in recent years there have been several new instruments capable of making these difficult measurements in the water. Our objective is to compare data from some of these instruments with the existing measurements and models and to examine its effects on underwater image quality. Specifically, we will first measure *complete* volume scattering functions (VSFs) in relevant coastal and littoral environments. These will then be combined with radiative transfer models to quantitatively determine their effects on imaging systems properties. We will also use these measurements in other Navy-funded imaging performance prediction tools to determine the operational effects that the different VSFs may have. We will then relate this to particle types and size distributions

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APPROACH

The critical element of this effort is obtaining high-quality, complete angular measurements of the volume scattering function. In imaging systems, it is both the near forward AND near-backward region of the VSF that affects visibility and imaging performance. We have been working with two VSF instruments, the Multi-spectral volume scattering meter (MVSM) and the Laser In-Situ Scattering and Transmissometry (LISST) to measure the VSF over nearly the entire angular range (0.07^{o} – 179°). The combination of these instruments has proven to provide accurate and reliable VSF measurements in a wide variety of oceanic, coastal, littoral, and riverine conditions.

The second part of this effort involves using these measured VSFs to calculate the properties commonly used in imaging analysis: the point-spread and modulation transfer functions (PSF, MTF). We will use two methods. The first is to solve the radiative transfer equation in the small-angle approximation [2-5]. This gives the MTF directly as function of the range R, the attenuation and scattering coefficients (c, b), and the Hankel transform of the VSF:

$$MTF(q,R) = \exp\left\{-R\left[c - b\overline{B}(q)\right]\right\},$$

where

$$\overline{B}(q) = \int_0^1 B(qt)dt \quad, \quad B(q) = 2\pi \int_0^\infty \tilde{\beta}(\theta)J_o(2\pi\theta q)\theta d\theta.$$

Here, $\tilde{\beta}(\theta)$ is the volume scattering phase function, q is the spatial frequency in cycles/radian, J_o is the zero-order Bessel function of the first kind, and B is the Hankel transform of the phase function. An additional Hankel transform of the MTF gives the point-spread function. The second approach will use previously developed Monte Carlo techniques [6] to calculate the point-spread function directly using the optical properties and VSFs. A Hankel transform of these PSFs gives the MTF. This provides a check on the small-angle methods and also lets us calculate the amount of backscattered light for each case.

The final step is to evaluate the effects of the measured VSFs on actual Navy underwater imaging systems. We will use the imaging performance prediction tool EODES (Electro-optic Detection Simulator) developed by Metron Scientific Solutions. This tool models the performance of a laser-line scanner system and produces quantitative predictions of image quality under operational conditions. The sensitivity of these models to environmental conditions is required to determine possible issues associated with denied access areas, where complete optical measurements are seldom available.

WORK COMPLETED

We have successfully measured volume scattering functions in a variety of oceanic, coastal, littoral and riverine areas relevant to the Navy. Areas we will examine include:
1) Monterey Bay, California
2) Puget Sound, near Everett, Washington
3) Hudson River Plume

We have also measured the volume scattering function of a solution of Maalox, which is commonly used in laboratory experiments as a scattering agent.

A previously created Monte Carlo program has been modified to read these measured functions and calculate the point spread function of the water, given the absorption and scattering coefficients and the range. Another program was written to numerically calculate Hankel transforms and determine the modulation transfer function from the PSF (and vice versa).

In addition to the Monte Carlo approach, the radiative transfer equation has been solved under the small-angle approximation and used to calculate the MTFs for each VSF. The same numerical Hankel transform is used to calculate the PSF. Comparisons between both approaches have been made.

RESULTS

Some examples of measured volume scattering phase functions at a wavelength of 532 nm are shown in Figure 1. The "average" particulate volume scattering function, as measured by Petzold and defined by Mobley [7] is included, as well as that used in the imaging simulations of Wells [1].
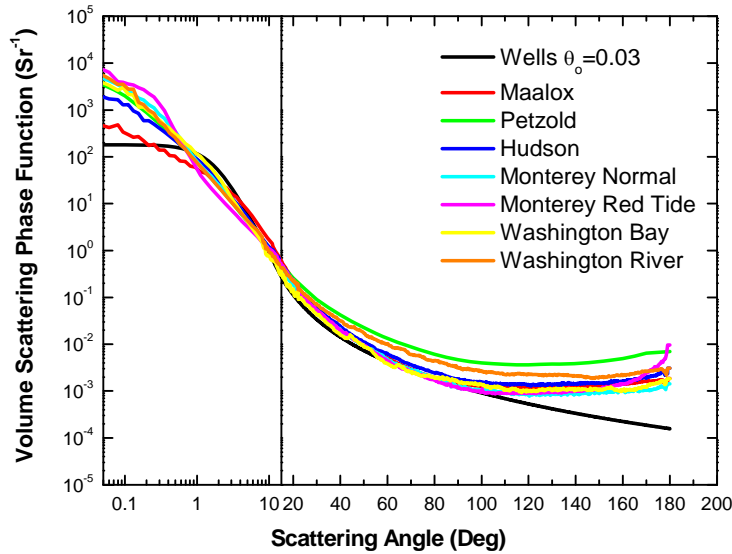

Figure 1. Volume scattering phase functions measured by the MVSM/LISST combination, along with the average particulate measurements by Petzold and the analytical one defined by Wells. The vertical line demarcates the transition of the ordinate scale from logarithmic to linear.

Now it is clear that the scattering functions of Maalox and Wells are quite different than the others: much less forward peaked, and Wells shows a significant drop-off in the backward directions. The other scattering functions can roughly be classified as follows. The Hudson River plume is near the transition between the river plume and ocean waters outside of New York harbor. It can be considered the most "ocean-like" of the measured functions. The Monterey Bay functions were measured inside and out of an algal bloom, and are labeled "Red tide" and "Normal." They are representative of an area dominated by biological particles. The Washington functions were measured in an estuarine system in the Snohomish River and its associated bay in the Puget Sound region. These are representative of minerogenic and sediment dominated areas.

The differences between these functions are indicative of the types and size distributions of the particles present in each region. In general, the Monterey functions show the largest peaks in the forward direction, and conversely the smallest values in the backward. The Washington functions also show large peaks at the forward angles, but with higher values in the backward. The Hudson function exhibits the smallest forward peak of the in-water functions and backward values that fall somewhere in the middle. In general terms, the near-forward values of the VSF are representing the size distributions of particles present: the larger peaks in the Monterey and Washington functions indicating a higher fraction of large particles. The near-backward values are more representative of the types of particles: higher average index of refraction particles in generally leading to larger values, as seen with the mineorogenic particles in the Washington river data. Note the Monterey Red tide function shows a significant backscattering peak near 180°. At this point, it is unknown if this is a real feature or an artifact of the measurement.
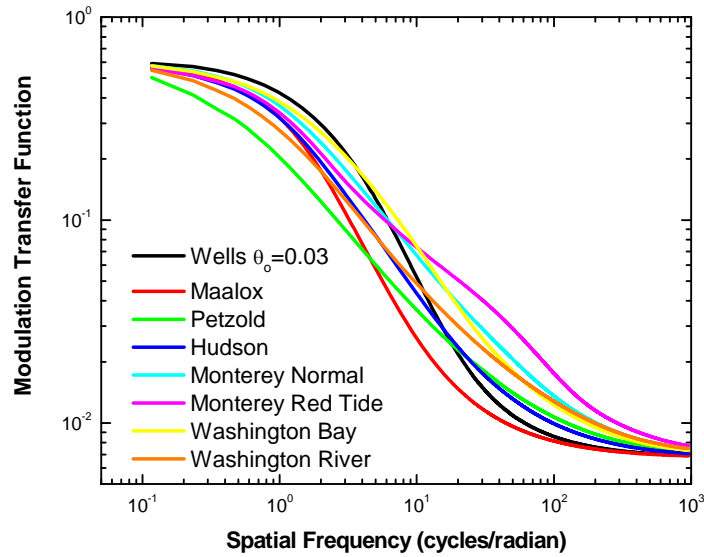

Figure 2. Modulation transfer functions calculated from the volume scattering functions. The optical depth is 5 and the single scatter albedo is 0.9. Note the results are plotted on a log-log scale.

With the volume scattering functions in hand, the modulation transfer functions have been calculated using the small-angle approximation to the radiative transfer equation. For brevity, we will only consider the small-angle approximation MTFs, and not those calculated using Monte Carlo methods. Differences between these approaches do exist, but they are generally small and perhaps better analyzed at a later time. Also, we do not expect significant differences between MTFs at smaller optical depths. In figure 2 we show the MTFs generated from the VSFs at an optical depth of 5 and a single scattering albedo of 0.9, typical values for the environments where imaging will be used.

While often times the MTF is normalized to give a value of unity at zero frequency, we are instead showing the un-normalized MTF to emphasize the relationship to the absorption and scattering coefficients. The low and high frequency limits are then fixed regardless of the VSF:

$$MTF(q = 0) \approx \exp(-aR), \qquad MTF(q \to \infty) = \exp(-cR).$$

The MTFs show some surprising variability. The largest differences occur in the frequency range of 10-100 cycles/radian. The "Red Tide" MTF shows the best high-frequency response, while the Maalox curve the worst. The other functions generally fill in the space between these two extremes. Looking back at the VSF curves in figure 1, we find the unsurprising result that the more forward-peaked VSFs lead to better high-frequency response. But what is surprising is the relatively poor high-frequency performance of the Petzold curve, as well as the Hudson, in relation to other measured functions.

The low frequency response is also of some interest. Looking at the range between 1 and 5 cyc/rad, we now notice that the Petzold curve has the *worst* low frequency response, followed by the Washington river curve, whereas the Wells curve gives the *best* response. The origin of this behavior appears to lie in the backscattering to forward scattering ratio, if we again refer back to figure 1. This will be investigated further.

Table 1. Modulation Transfer Function values at selected spatial frequencies for different volume scattering functions

Spatial Freq. (cyc./rad.)	Wells	Maalox	Petzold	Hudson	Mont. Norm.	Mont. Red Tide	Wash. Bay	Wash. River
1	0.415	0.310	0.198	0.310	0.357	0.329	0.376	0.269
10	0.0519	0.0260	0.0360	0.0433	0.0667	0.0732	0.0740	0.0485
100	0.00857	0.00815	0.0107	0.00992	0.0136	0.0176	0.0123	0.0128
1000	0.0069	0.0069	0.0072	0.0071	0.0074	0.0077	0.0073	0.0075

A quantitative comparison of the MTF values for the different VSFs is shown in Table 1 for some select frequencies. Notice the MTFs from the different VSFs can vary by more than a factor of 2.

IMPACT/APPLICATIONS

These measurements show the variability of the volume scattering in coastal and littoral areas, and, in many cases, the inadequacy of current models to account for this variability. The low-frequency performance, which is most closely related to the detection of an object, appears to be a function of the particle composition in the region, whereas the high-frequency response, more closely associated with the identification of an object, appears to be a function of the particle size distribution. We must point out that these effects are the result of an "everything else being equal" hypotheses. Also, this analysis does not yet take into account the system parameters, such as signal-to-noise ratios, which will have a measurable effect on the results. However the variability exhibited here suggests that a using only a single volume scattering function in performance predictions models may be inadequate. This points to the need to understand quantitative effects of other properties on the VSF and how the Navy could obtain such information.

TRANSITIONS

Some preliminary volume scattering function data has been supplied to Metron Scientific solutions (Tom Giddings) for their image simulation and validation. Other volume scattering functions have been supplied to NAVAIR (Linda Mullen) for similar underwater image work.

RELATED PROJECTS

Measurements of volume scattering functions are being collected and provided as part of NRL core projects entitled "Determining all inherent optical properties of coastal waters with an off-nadir airborne optical hyperspectral sensor" and "Lidar and hyperspectral remote sensing of the littoral environment."

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PUBLICATIONS

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